(2)

AD-A242 686

WL-TR-91-4027

SELF-DIRECTED CONTROL OF END MILLING

Barry K. Fussell & Douglas P. Gagne
University of New Hampshire

Nov 1991

Final Report for the Period May 1989 - October 1990

Approved for public release; distribution is unlimited.

MATERIALS DIRECTORATE
WRIGHT LABORATORY
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433-6533

91-15880

NOTICE

WHEN GOVERNMENT DRAWINGS, SPECIFICATIONS, OR OTHER DATA ARE USED FOR ANY PURPOSE OTHER THAN IN CONNECTION WITH A DEFINITELY GOVERNMENT-RELATED PROCUREMENT, THE UNITED STATES GOVERNMENT INCURS NO RESPONSIBILITY OR ANY OBLIGATION WHATSOEVER. THE FACT THAT THE GOVERNMENT MAY HAVE FORMULATED OR IN ANY WAY SUPPLIED THE SAID DRAWINGS, SPECIFICATIONS, OR OTHER DATA, IS NOT TO BE REGARDED BY IMPLICATION, OR OTHERWISE IN ANY MANNER CONSTRUED, AS LICENSING THE HOLDER, OR ANY OTHER PERSON OR CORPORATION; OR AS CONVEYING ANY RIGHTS OR PERMISSION TO MANUFACTURE, USE, OR SELL ANY PATENTED INVENTION THAT MAY IN ANY WAY BE RELATED THERETO.

THIS REPORT IS RELEASABLE TO THE NATIONAL TECHNICAL INFORMATION SERVICE (NTIS). AT NTIS IT WILL BE AVAILABLE TO THE GENERAL PUBLIC, INCLUDING FOREIGN NATIONS.

THIS TECHNICAL REPORT HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION.

STEVEN R. LECLAIR, Major, USAF
Technical Director, Manufacturing Research
Integration and Operations Division
Materials Directorate

WALTER M. GRIFFITH
Branch Chief, Manufacturing Research
Integration and Operations Division
Materials Directorate

FOR THE COMMANDER

IF YOUR ADDRESS HAS CHANGED, IF YOU WISH TO BE REMOVED FROM OUR MAILING LIST, OR IF THE ADDRESSEE IS NO LONGER EMPLOYED BY YOUR ORGANIZATION PLEASE NOTIFY WL/MLIM, WRIGHT-PATTERSON AFB, OH 45433-6533 TO HELP MAINTAIN A CURRENT MAILING LIST.

COPIES OF THIS REPORT SHOULD NOT BE RETURNED UNLESS RETURN IS REQUIRED BY SECURITY CONSIDERATIONS, CONTRACTUAL OBLIGATIONS, OR NOTICE ON A SPECIFIC DOCUMENT.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
November 1991

3. REPORT TYPE AND DATES COVERED
Final May 1989 - October 1990

4. TITLE AND SUBTITLE
Self-Directed Control of End Milling

5. FUNDING NUMBERS
Contract Number:
S-210-9MG-064
PE 61102F
PR 2418
TA 05
WU 54

6. AUTHOR(S)
Barry K. Fussell and Douglas Gagne

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of New Hampshire
Durham, New Hampshire

8. PERFORMING ORGANIZATION REPORT NUMBER
NA

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Manufacturing Research Branch
Materials Directorate
Wright Laboratory
Wright-Patterson AFB, OH 45433-6533
(WL/MLIM/Maj Steven R. LeClair (513)255-8787)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
WL-TR-91-4027

11. SUPPLEMENTARY NOTES
The computer software contained herein are "harmless", already in the public domain.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for Public Release
Distribution Unlimited

12b. DISTRIBUTION CODE

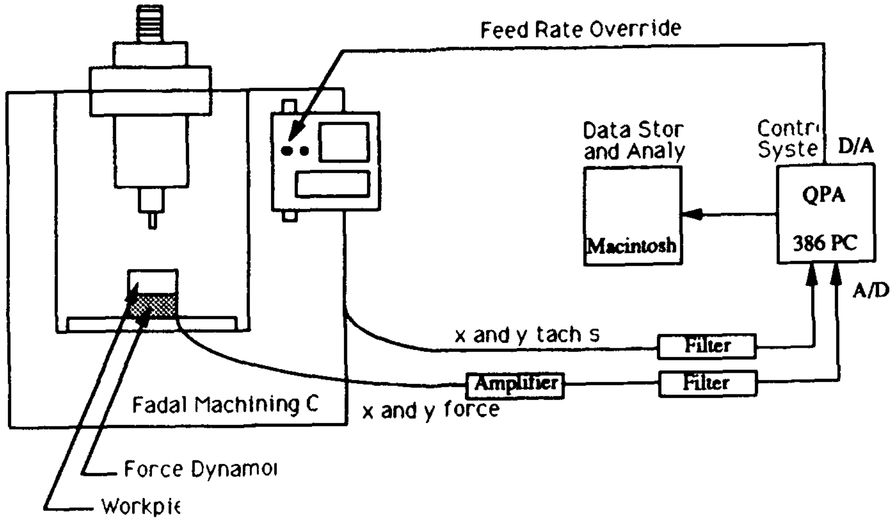
13. ABSTRACT *(Maximum 200 words)*
Self-directed control is a closed-loop control philosophy using qualitative techniques to achieve real-time generation of a process control cycle. One such instance of self-directed control is Qualitative Process Automation (QPA). This report presents the results of applying QPA to the end milling machining process to maximize feed rates while avoiding the undesirable cutting events of excessive tool deflection, tooth overload and cutter shank overload. QPA is a real-time controller with its control output based on process events and not on temporal relationships as are classical machine tool control systems. Various procedures for detecting machining events with sensor data were investigated and used with QPA to develop a controller for the end milling process. The QPA controller used cutting force, spindle speed and feed rate data to predict and avoid excessive tool and tooth loads and to maintain part tolerance with the highest possible feed rate. Simulation cutting results, using an experimentally validated end milling model showed the QPA system to be successful in controlling end milling cuts for step changes in the radial and axial depths of cut on aluminum workpieces. Experimental cutting results validated potential of QPA.

14. SUBJECT TERMS

15. NUMBER OF PAGES
35

16. PRICE CODE

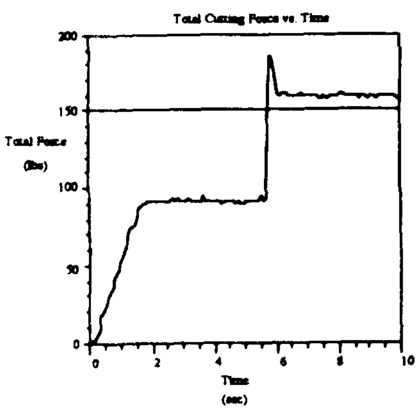
17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

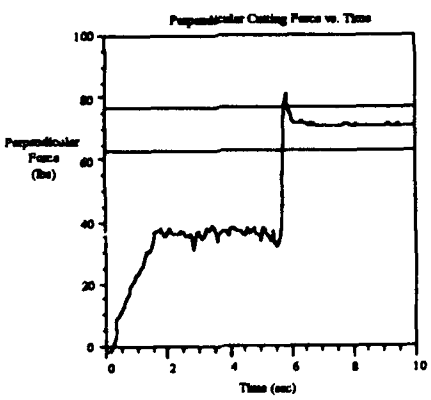


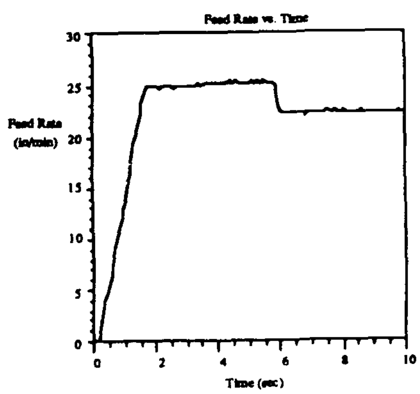
Self-Directed Control of End Milling

by

Barry K. Fussell, Ph
and
Douglas P. Gagne







University of New Hampshir

1989 RESEARCH INITIATION PROGRAM

Sponsored by the

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

Conducted by the

Universal Energy Systems, Inc.

FINAL REPORT

Self-Directed Control of End Milling

Prepared by:	Barry Fussell, Ph.D Douglas Gagne
Academic Rank:	Assistant Professor Research Assistant
Department and University:	Department of Mechanical Engineering University of New Hampshire

Date:	24 October, 1990
Contract No:	S-210-9MG-064

Self-Directed Control of the End Milling Process

by
B.K. Fussell
D.P. Gagne

Abstract

Self -directed control is a closed-loop control philosophy using qualitative techniques to achieve real-time generation of a process control cycle. One such instance of self-directed control is Qualitative Process Automation (QPA). This report presents the results of applying QPA to the end milling machining process to maximize feed rates while avoiding the undesirable cutting events of excessive tool deflection, tooth overload and cutter shank overload. QPA is a real-time controller with its control output based on process events and not on temporal relationships as are classical machine tool control systems. Various procedures for detecting machining events with sensor data were investigated and used with QPA to develop a controller for the end milling process. The QPA controller used cutting force, spindle speed and feed rate data to predict and avoid excessive tool and tooth loads and to maintain part tolerance with the highest possible feed rate. Simulation cutting results, using an experimentally validated end milling model showed the QPA system to be successful in controlling end milling cuts for step changes in the radial and axial depths of cut on aluminum workpieces. Experimental cutting results validated the simulation results and further demonstrated the potential of QPA.

Acknowledgments

We would like to thank the Air Force Systems Command, the Air Force Office of Scientific Research, Major Steve LeClair of the Materials Lab and Rick Matejka of Universal Technology Corporation, for making this research effort possible. Thanks also go to Universal Energy System for managing the project.

I. Introduction

One of the major thrusts in manufacturing research is improved control of material processing operations. Through such control, the material quality is enhanced and the fabrication time is reduced, leading to a higher production rate and fewer part rejects. Initial Air Force research in this area has been the development of a control philosophy know as self-directed control which was implemented in a system referred to as Qualitative Process Automation (QPA) to control an autoclave during curing of graphite-epoxy composites. The Air Force Materials Laboratory has shown that a closed-loop, "event-driven" controller such as QPA can significantly reduce the composite curing time while consistently yielding the desired part quality [1].

This first success of QPA has encouraged the Air Force to apply self-directed control to a very different type of process, one where the speed of response of the control system is much more demanding. One such process is the cutting of metals on a machining center. Metal cutting is a very fast process that is time-varying and nonlinear in nature. As a result, it is very difficult to control by classical methods and therefore lends itself to self-directed control, i.e, control by events rather than by temporal prescription.

The end milling process has been very difficult to model and even more difficult to control. Research experience has shown that classical, empirical and adaptive methods meet with some success, but have many shortcomings. With this in mind, the authors propose to combine this knowledge of the cutting process with the QPA system to see if event-driven control of end milling is feasible, using both computer simulation and experimental results for verification.

II. Objectives of the Research Effort

The research objective was to determine the feasibility of QPA control of processes very different from the autoclave curing of graphite-epoxy composites. In particular, QPA was applied to the end milling machining operation to see if part quality could be improved while reducing the machining time. Successful demonstration of this control system would prove the robustness of self-directed control as opposed to conventional control systems, and provide a path for more diverse applications.

QPA was considered for the machining process because of the significant gains possible in Adaptive Manufacturing Systems (AMS). In addition to reduced machining times, self-directed control would also augment the machine operator in maintaining part quality and insuring safe machine operation, e.g. where the machining center is unmanned and must depend on sensor input to determine part quality and machine diagnostics.

Self-directed control would enable varying the feed drive and spindle speed to maintain the part surface finish and tolerance while avoiding chatter and catastrophic tool failure. In order to provide this capability the milling process had to be translated into the QPA process representation structure. This required defining the process schedule in terms of events, i.e. episodes and states associated with the milling process. Particular attention had to be paid to developing a list of achieve and prevent episodes and conditions to detect them.

In preparation of this research a literature review was undertaken to determine the various methods of detection. Feasibility of self-directed control was evaluated by simulation of the end milling process using the Advanced Continuous Simulation Language (ACSL). The simulation model accepts feed drive and spindle speed inputs and determines the resulting cutting forces and deflections. The simulation results were intended as proof of concept as opposed to a rigorous evaluation of self-directed control.

After the feasibility of self-directed control was determined by simulation, experimental testing was performed to demonstrate the actual control of end milling on a CNC machining center. Again, fairly simple cuts were made so that the QPA system could be evaluated. The difficulty of applying the QPA system to a real machining center was also addressed along with recommendations and conclusions.

III. QPA

The QPA system was first demonstrated in 1986 for control of the composite curing process at Wright Patterson AFB [1] and was based on Qualitative Process Theory developed by Dr. Kenneth Forbes [3]. The basis of the QPA system is that the process is controlled by events as opposed to temporal prescription. By using events, the set points for the inner loop control of the autoclave process can be adjusted to insure that desired events, denoted by episodes or states, are achieved and those causing failure are prevented.

The autoclave process has inner-loop control of pressure and temperature and an outer-loop control to generate a temperature profile such that the part is cured properly. Typical achieve episodes are cure and compaction while typical prevent episodes are voids and accelerated reaction. These episodes are predicted by process states and are sequentially carried out to complete the history of the curing cycle.

Detection of various process states is enabled by sensors embedded in the product and process agent. The detection of events is critical and hence sensor information is necessary. This is true of the autoclave process as well as any other process that is to be controlled using self-directed control. When conflicts arise between achieve episodes, an expert's knowledge in the form of rules is utilized to resolve the conflict. Decisions are then carried out by system controllers, i.e. the heating system is turned up or down such that a good composite is produced.

The QPA language is composed of object types whose relationships form a qualitative model of the process (see Figure 1) [4]. The process history is defined as the sequence of events needed to transform an original part to its final form. The events are composed of episodes that contain prevent and achieve states (process instances) that cause the desired changes in the part. A process instance is utilized to determine when an event occurs, while the process library determines how to respond to that event.

The controllers and sensors are the interface between the QPA knowledge base and the process. The sensor module of the QPA system receives data from a physical device connected to the system or through a mathematical model that simulates the behavior of the device. The choice of whether to use the actual sensor data or mathematically derived values is based on the sensor reliability and user defined acceptance levels. Sensor data is used to indicate the state of a process (start or finish) and how it should be influenced by the process library. To make certain that the processes are controlled properly requires the use of influence instances (Figure 2). Influences are qualitative relationships that indicate how changes in one sensor or controller will affect another. Positive influences define proportional relationships between two parameters while negative influences indicate those that are inversely proportional. This information is utilized in determining what and how much controller action is necessary to achieve desired events, or prevent undesired events.

IV. QPA Control of End Milling

End Milling Model

A block diagram of end milling process dynamics is shown in Figure 3 [5], and corresponds to the various components of a machining center. There are two major, or primary process dynamics. The first is the feed and spindle dynamics. Here, a reference signal is used to generate a slide velocity in the x and y directions, and a spindle speed. The second is the cutting process, which includes geometry of the cut and the force required to remove the material. The geometry of the cut is a combination of the slide and spindle speed, workpiece geometry, tool geometry, and the deflection of cutter from the workpiece. The deflection results from the cutter force acting on the workpiece, tool and machine, and is illustrated in Figure 3 as the structure compliance. The resulting deflection causes two feedback paths that affect the cut geometry. The instantaneous feedback causes a reduction in the chip thickness that has to be removed by the next tooth. This effect is shown in the delayed feedback loop, better known as the regenerative loop. Since this is a positive feedback, it can lead to an instability known as chatter.

A computer program previously written [5] uses the mathematical relationships associated with the process dynamics to calculate the resulting force for a given slide and spindle

speed, and cutting geometry. Experimental end milling cuts on a CNC machining center [5] have been used to verify the simulation model for a variety of cutting conditions.

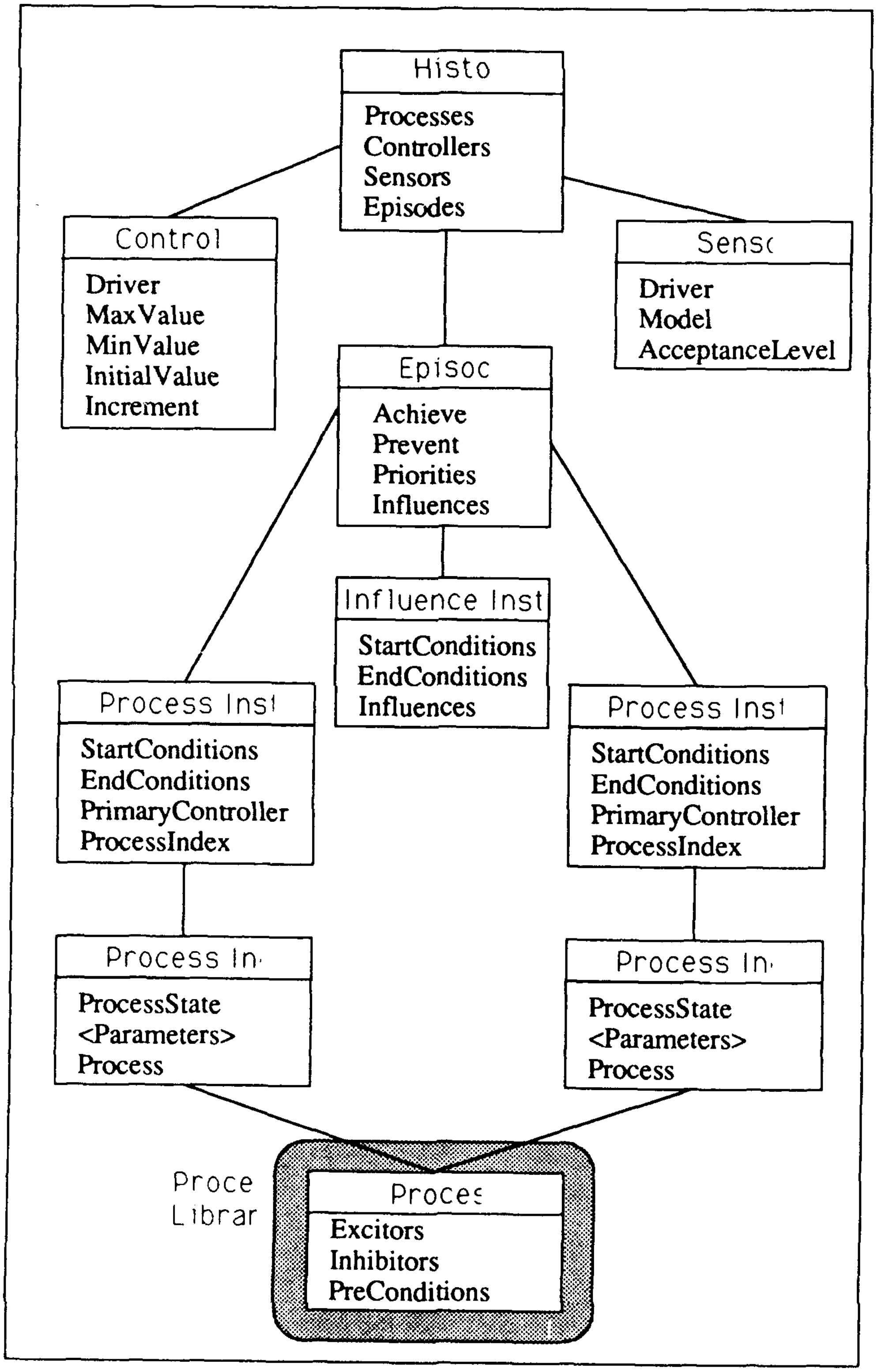


Figure 1 - Hierarchical Structure of QPA Objects

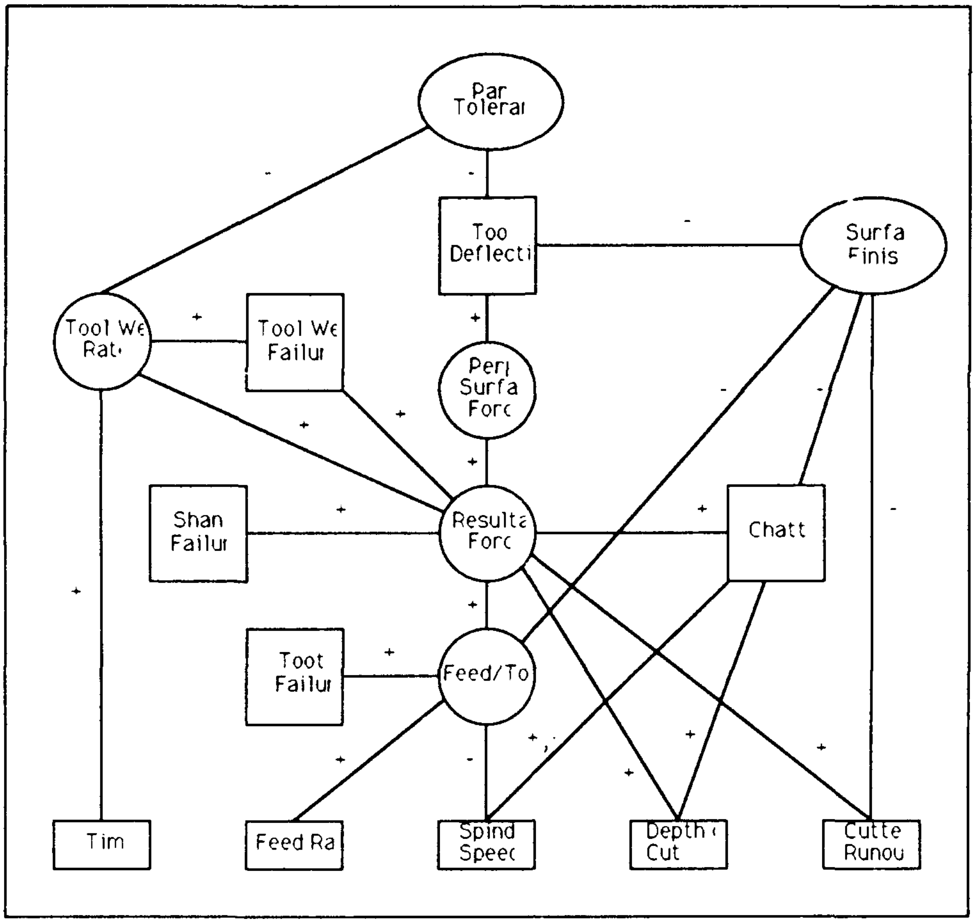


Figure 2 - End Milling Influence Diagram

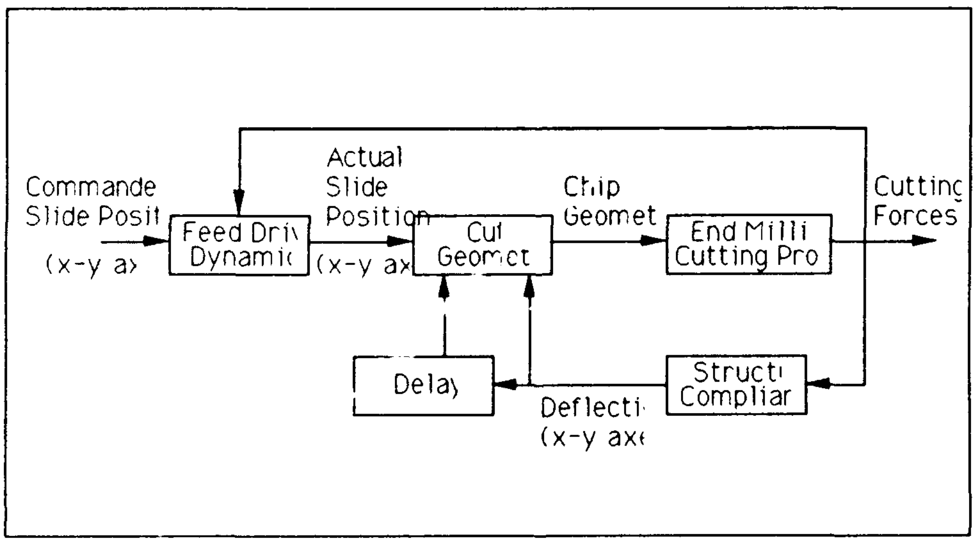


Figure 3 - End Milling Block Diagram

QPA Structure

Figure 4 shows the QPA structure (organization of the knowledge base) for a general machining operation. The history or process plan of the part is the complete cutting routine, while the various episodes are composed of the different tools used to make the cutting history. Examples here would be end milling, face milling, boring and drilling operations. Under each episode are the events that are desired (achieve) and those to be avoided (prevent). Since end milling is the operation that is being evaluated, only one episode is considered, along with its associated events of maximum feed rate, shank failure, tooth failure, tool wear failure, tool deflection and chatter. The desired goal during this episode is to complete the end milling cut in the shortest amount of time while avoiding the undesired events. While a very fast cut is desired, both a good finish and part tolerance are also desired. Since neither of these quantities can be measured directly by sensors, they are inferred by qualitative relationships between events and/or sensed conditions, e.g. temperature, force, vibration, etc. For example, to insure part tolerance, excessive deflection of the tool is prevented by monitoring the cutting force perpendicular to the feed path, and reducing the feed rate if the force and hence the deflection becomes excessive. Likewise, the surface finish can be inferred from the spindle speed, feed rate, tool deflection and chatter state.

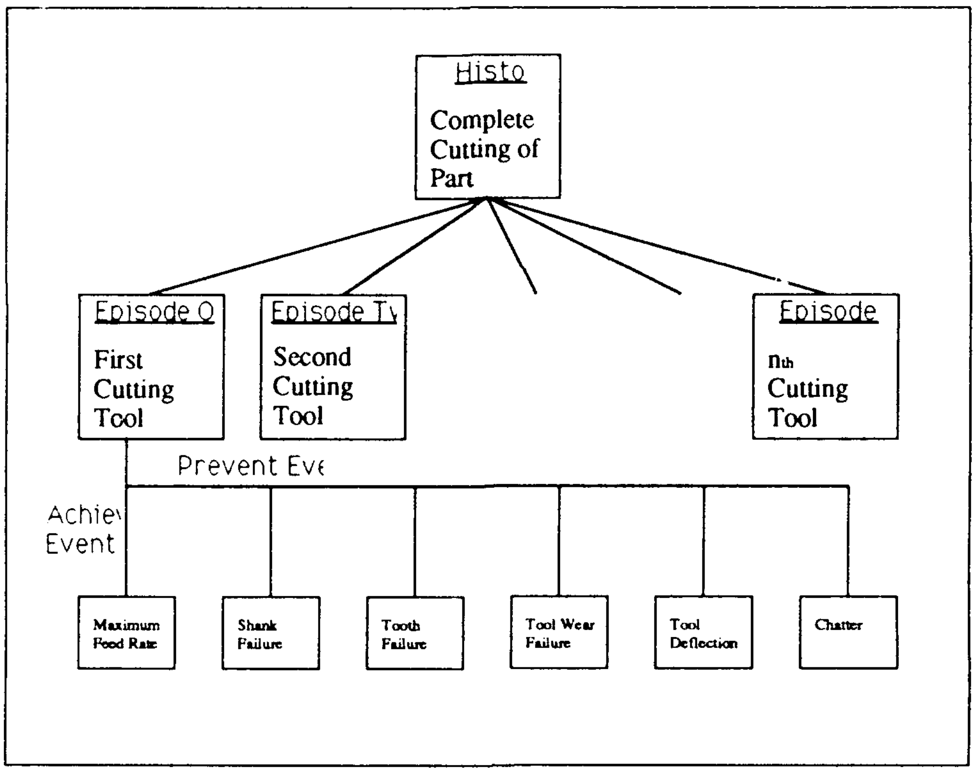


Figure 4 - QPA Control Structure for the End Milling Process

Utilization of these described events and conditions for control requires an event detection, an influence diagram, and conflict resolution rankings. Unfortunately, the event detection is not straightforward because of indirect sensing, i.e. the lack of sensor availability. Indirect sensing refers to the prediction of an event such as tooth failure or chatter through sensory data not directly associated with the event. For example, tooth failure cannot be predicted by a tooth failure sensor, it has to be inferred from the cutting force or acoustic emissions. In a similar fashion, the onset of all the other prevent events must be determined by indirect sensory data and detection algorithms. These algorithms can be quite complex and involved and often times are limited in their application to fairly simple cuts. None-the-less, one

can develop a set of tools to predict the onset of various events through the use of cutting force, spindle speed, feed rate and acoustic emissions, etc. A description of the various events and associated conditions, possible detection algorithms, and the necessary control action is given below.

Events and Associated Detection Methods

1. Tooth and Tool Breakage

A method of in-process detection of tooth breakage was developed by Altintas et al. [6] and Altintas and Yellowley [7]. They use the first and second differences of the resultant cutting force, shown below, averaged over one tooth period, to predict breakage.

$$\Delta_1 F_a(t) = F_a(t) - F_a(t-1) \qquad (1)$$

$$\Delta_2 F_a(t) = \Delta_1 F_a(t) - \Delta_1 F_a(t-1) \qquad (2)$$

To utilize the first and second difference equations, a threshold relationship is derived to eliminate the disturbance effects of radial immersion and runout. The radial immersion is predicted, if not known in the cut, and used in the following threshold relationship.

$$\Delta' F_a = \frac{F_a(t) - F_a(t-1)}{F_a(t-1)} \qquad (3)$$

By comparing the value of this relationship during a cut to that predicted by a simulation model, a triggering of the second difference is initiated. If the second difference of the average force is found to be larger than the first difference, then tooth damage is assumed. Another method is given in [8].

2. Tool Breakage Prevention

To prevent the cutting tool from breaking at the shank, the total force on the cutting tool can be monitored and limited to some maximum value. This maximum force limit can be roughly calculated by applying standard shaft theory to the cutting tool. Equations 4 and 5 give the stress state of the cutting tool as a function of applied load and tool geometry. The highest stress magnitudes occur on the outside of the tool at the supported end where there is a combination of normal and shear stresses.

$$\sigma_b = \frac{32\,F\,L}{\pi\,D^3} \qquad (4)$$

$$\tau = \frac{8\,F}{\pi\,D^2} \qquad (5)$$

where, σ_b ≡ Maximum bending stress, Psi

τ ≡ Maximum shear stress, Psi

F ≡ The applied force on the beam, lbs

L ≡ Length of the tool, in

D ≡ Diameter of the tool, in

Now, by using a Mohr's circle and the Maximum Shear-Stress Theory of failure, an upper limit of the applied force can be calculated. The maximum shear stress is given by Equation 6.

$$\frac{S_y}{2n} > \tau_{max} = \sqrt{\left(\frac{\sigma_b}{2}\right)^2 + \tau^2} \tag{6}$$

where, S_y ≡ Yield Strength of the cutting tool material, Psi

n ≡ Factor of safety

The upper limit for the force bandwidth can now be found by substituting Equations 4 and 5 into Equation 6 and solving for the force, F. The resulting relationship is shown below.

$$F_{max} = \frac{S_y \pi D^2}{16\, n \sqrt{4\left(\frac{L}{D}\right)^2 + 1}} \tag{7}$$

where, F_{max} ≡ Upper limit of bandwidth

The lower limit should make the bandwidth large enough so any force oscillations remain within the limits.

The sensor information available to QPA is the force in the x- and y-directions. With these values known, the resultant total force on the cutting tool can be computed as shown in Equation 8.

$$F_{total} = \sqrt{\left(F_x{}^2 + F_y{}^2\right)} \tag{8}$$

If a shank overload is experienced, the controller actions need to decrease the total force on the tool by decreasing the feed rate or increasing the spindle speed. Both actions result in a decrease in the chip size which, in turn, decrease the forces on the tool.

3. Tooth Breakage Prevention

To prevent tooth failure, a similar analysis as shown in the previous section on shank failure can be performed. The following method, developed by Melkote and Taylor [9], is a procedure to determine the maximum feed per tooth allowed for a given cutter and cutting situation. The tooth of the cutting tool is assumed to be a cantilever beam with a point load at midpoint of the axial depth. Figure 5 shows the tooth geometry and the loading conditions. The point load in Figure 5 can now be replaced by the same point load at the center of the tooth edge, point C, and moment applied at the same location.

The magnitude of the moment can be calculated by summing the forces and moments. The resulting moment is given by Equation 9.

$$M = \frac{F\,(l\text{-}d)}{2} \tag{9}$$

where, M ≡ Moment needed to move force to center of tooth edge, lb-in

F ≡ Force applied to tooth, lb

l ≡ Length of tooth, in

d ≡ Axial depth of cut, in

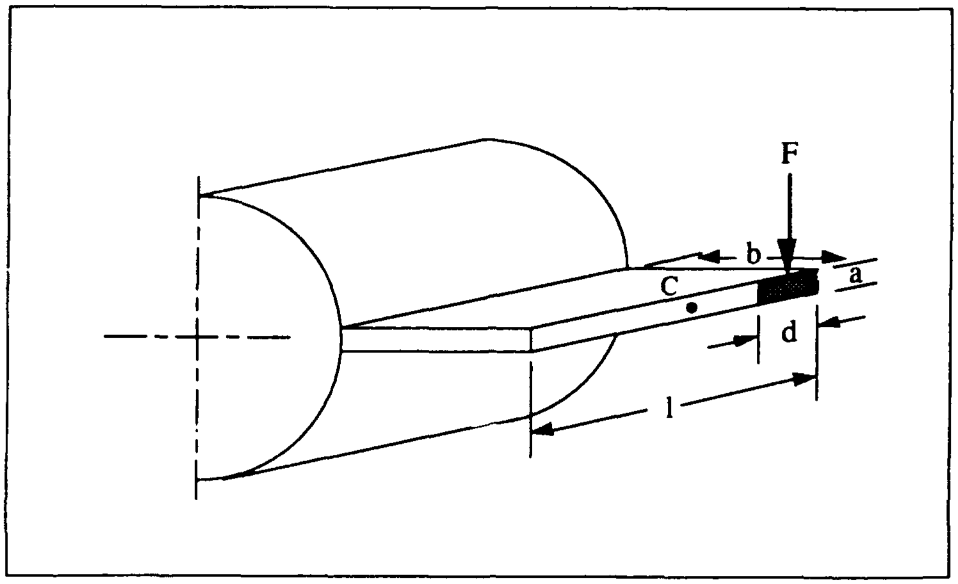


Figure 5 - Tooth Geometry and Loading

The resulting tooth load is shown in Figure 6.

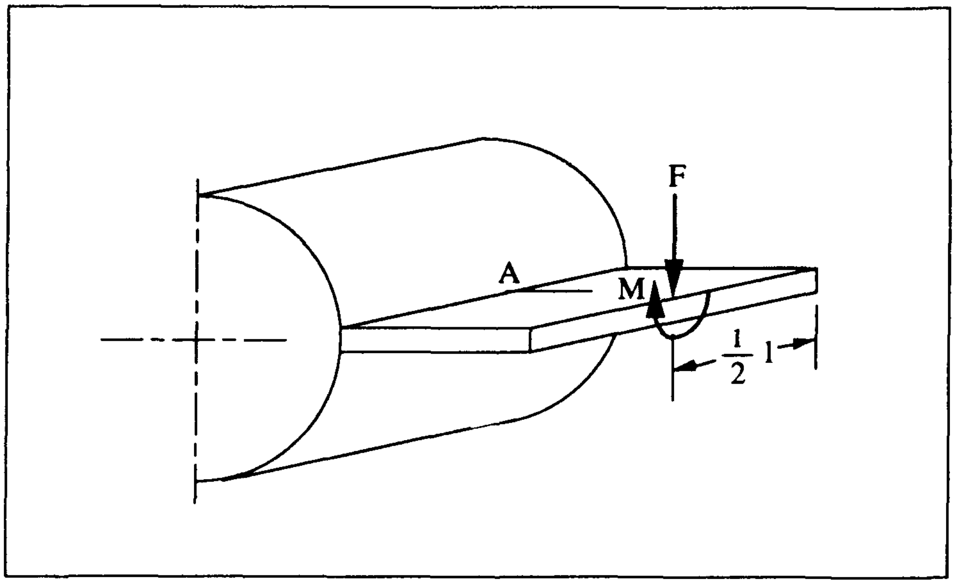


Figure 6 - Tooth Load Including Moment

It is now necessary to calculate the stress state in the beam. Using simple beam analysis, the stress created from the force F at point A in Figure 6 is given by Equation 10.

$$\sigma_b = \frac{6\,F\,b}{a^2\,l} \tag{10}$$

where, σ_b ≡ Maximum bending stress, Psi
b ≡ Width of tooth, in
a ≡ Thickness of tooth, in
l ≡ Length of tooth, in

The torsional moment M causes a maximum shear stress at point A and has a magnitude given by Equation 11 [10].

$$\tau = \frac{F\,(l-d)\,(3\,l + 1.8\,a)}{2\,l^2\,a^2} \tag{11}$$

where, τ ≡ Maximum shear stress, Psi

The assumptions needed to use Equation 11 are a straight bar with a rectangular cross section. The moments applied to the beam must be equal and opposite end couples and the ends must be free to warp. The tooth geometry satisfies all these assumptions except that the end connected to the shaft of the tool is not free to warp. Investigations were made to derive a new equation which allows a constrained end but the results were inaccurate, giving a lower stress than the one calculated with Equation 11. Equation 11 does allow a quick approximation of the shear stresses in a tooth, however, more work is needed to accurately determine the allowable limits on tooth forces.

By using the same method as the previous section, the maximum shear stress can be found by Equation 12.

$$\frac{S_y}{2n} > \tau_{max} = \sqrt{\left(\frac{\sigma_b}{2}\right)^2 + \tau^2} \tag{12}$$

The limiting tooth force can be found by substituting Equations 10 and 11 into Equation 12 and solving for F. The result is shown in Equation 13.

$$F = \frac{S_y\,a^2\,l}{6\,b\,n\sqrt{1 + \frac{(l-d)^2\,(3\,l + 1.8\,a)^2}{36\,b^2\,l^2}}} \tag{13}$$

The horsepower needed to overcome the force F at a given tooth speed, V, is given by Equation 14.

$$P = \frac{F\,V}{33000} \tag{14}$$

where, P ≡ Horsepower needed, hp
F ≡ Tooth Load, lbs
V ≡ Tooth Speed, ft/min

The tooth speed can be found by Equation 15.

$$V = \frac{\Omega\, 2\pi\, D}{12} \tag{15}$$

where, V ≡ Tooth Speed, ft/min
Ω ≡ Spindle speed, RPM
D ≡ Cutting tool diameter, in

The horsepower lost in material removed is estimated by Equation 16 [9]

$$P = K\, Q^{3/4} \tag{16}$$

where, K ≡ Material constant, hp/(in^3/min)
Q ≡ Rate of stock removal, in^3/min

The quantity K is a function of the workpiece and tool materials and type of cutter. It ranges from 0.2 hp/(in^3/min) for Aluminum to 3.5 for high-strength alloys [11]. The rate of stock removal, Q, is given by Equation 17.

$$Q = f_t\, N_f\, \Omega\, d\, W \tag{17}$$

where, f_t ≡ Feed per tooth, in/tooth
N_f ≡ Number of teeth on tool
Ω ≡ Spindle speed, RPM
d ≡ Axial depth of cut, *in*
W ≡ Width of cut, in

By equating Equations 14 and 16, the maximum feed per tooth can be calculated. The resulting relationship follows in Equation 18.

$$f_{t_{max}} = \frac{7.95 \times 10^{-9}}{N_f\, \Omega\, d\, W} \left(\frac{S_y\, a^2\, l\, \Omega\, D\, \pi}{K\, b\, n \sqrt{1 + \frac{(l - d)^2 (3\, l + 1.8\, a)^2}{36\, b^2\, l^2}}} \right)^{4/3} \tag{18}$$

This value is again used as the upper limit for the bandwidth. The lower limit is less critical, but should be large enough such that all feed per tooth oscillations remain within limits.

The actual feed per tooth value that must be calculated by the controller is a function of feed rate, spindle speed and tool geometry and is shown in Equation 19.

$$f_t = \frac{v_s}{\Omega\, N_f} \tag{19}$$

where, f_t ≡ Feed per tooth, in/tooth
v_s ≡ Feed Rate, in/min
Ω ≡ Spindle Speed, RPM
N_f ≡ Number of teeth on tool

The same controller actions used for shank failure are necessary for excessive feed per tooth values. A decrease in feed rate or an increase in spindle speed will result in a lower feed per tooth value.

4. Tool Deflection

Tool deflection is associated with the part tolerance and must be held below a predetermined limit. The amount of tool deflection can typically be inferred from the cutting force that is perpendicular to the feed rate direction [12]. By assuming the tool is a cantilever beam, Equation 20 can be used to predict the deflection, given the load and tool geometry [13].

$$y_{max} = \frac{F_{perp} L^3}{3 E I} \quad (20)$$

where, y_{max} ≡ Displacement at the free end of the tool, in

F_{perp} ≡ Force perpendicular to the feed rate, lbs

L ≡ Cutting tool length, in

E ≡ Modulus of Elasticity, Psi

I ≡ Area moment of inertia, in^4

Solving for the perpendicular force and considering the area to be a circle results in Equation 21.

$$F_{perp\text{-}max} = \frac{3\, y_{tol}\, \pi\, D^4\, E}{64\, L} \quad (21)$$

where, $F_{perp\text{-}max}$ ≡ Upper limit of tool deflection bandwidth, lbs

y_{tol} ≡ Allowable tolerance, in

D ≡ Cutting tool diameter, in

The lower limit should again be such that force oscillations are contained within the limits.

The controller must have access to at least two-dimensional force sensor data and two-dimensional feed rate sensor data to be able to calculate the perpendicular force. If the feed rate in one direction is zero, the perpendicular force is simply read directly from the force sensor in that direction. However, if the feed rate has components in both directions, the feed rate vector must be calculated and used to find the perpendicular component of the total force vector. Again, as with the previous sections on shank and tooth failure, decreasing the feed rate or increasing the spindle speed will result in a decrease in the perpendicular force on the cutting tool.

5. Chatter

Chatter is a complicated self-excited vibration that is very difficult to predict a priori. While it can be detected in-situ, it is not easy to determine what course of action to take to eliminate chatter and still maintain an aggressive cut. Smith and Tlusty [14] provide a method for determining the necessary system changes. Their algorithm is discussed below.

A force dynamometer or a directional microphone can be used to detect the presence of chatter. However, the best detection is afforded by using both sensors; the dynamometer to give indication of force oscillations and the microphone to give the frequency content. Chatter detection is made by checking the following criteria.

$$F_R > F_{R(\text{set point})} \tag{22}$$

$$\omega(\phi_p) \neq \omega_t \tag{23}$$

$$|\phi_p| > |\phi_t| \tag{24}$$

where, F_R ≡ Cutting force oscillation amplitude

ϕ_p ≡ Maximum power spectral density (PSD)

ω_t ≡ Tooth frequency

ϕ_t ≡ PSD at the tooth frequency

Equation 22 states that the force oscillation amplitude is higher than a predetermined set point. Equation 23 indicates that the frequency of the power spectral density (PSD) peak is not equal to the tooth frequency. Finally, Equation 24 requires that the PSD peak away from the tooth frequency is greater than PSD at the tooth frequency. If all 3 equations are satisfied, then chatter exists and some action must be taken. The action is now described.

The first step is to decrease feed rate. This reduces oscillation amplitudes as a result of chatter. Second, the spindle speed is increased if the frequency of the PSD peak point is greater than the tooth frequency, and decreased if the PSD peak point is less than the tooth frequency. If chatter still exists, then the axial depth of cut is decreased. Finally, the feed rate is increased. The purpose behind the spindle speed changes is to run the end mill at the system natural frequency, which gives a very high axial depth limit on stability.

Pattern Recognition and Neural Nets

Because of the difficulty in detecting the above described events using simple algorithms, several researchers are now pursuing sensor fusion techniques involving pattern recognition with artificial neural networks. These techniques appear to be more promising because information from many sensors is used to develop the weightings necessary to recognize the undesired events. For example, cutting force, cutting torque, and acceleration information of the spindle and quill are used to predict tool life, chatter, stable cutting and the tool entering a workpiece by M.A. Elbestawi and J. Marks [15].

In their work a set of d features, an example being the average cutting force, based on the force, torque, and acceleration information is used to find the weighting coefficients w_i in the relationship:

$$g_i = \sum_{k=1}^{d} w_{iK} x_K + w_{i,d+1} \tag{25}$$

so that the i^{th} class or event, e.g. tool life, can be recognized during an end milling cut. The weightings are originally found by using several experimental cutting trials where the desired event such as tool life, is known to occur. With this experimental information an error-correction procedure is applied to Equation 25 to find the best value for the weighting parameters. Preliminary results by Elbestawi show that correction rates of 80% to 100% can be obtained for the prediction of the four events.

Unfortunately, pattern recognition using artificial neural networks needs an extensive amount of research and testing before they will be useful in an intelligent machining application. Elbestawi's work is clearly a step in the right direction, but it lacks in predicting many of the undesired events in end milling, and in handling transient conditions resulting from changes in

the spindle speed and radial depth of cut. Also, real time implementation of the algorithms needs investigation.

There has also been some research into artificial neural network diagnostic methods for turning. Turning has actually been used as the original test bed of these techniques because of the continuous cutting action. Milling has discontinuous cutting, which makes it much more difficult to work with. Hopefully, some of the work described below will eventually be adapted to end milling.

Dornfeld and Pam [16] used pattern recognition techniques to determine the chip formation state using acoustic sensor information. This was followed with an article by Rangwals and Dornfeld [17] in 1987 on neural net usage in the detection of tool wear states. Also in 1987, Emel and Kannateg-Asibu [18,19] published results on tool fracture, wear and chip disturbance monitoring by pattern recognition using acoustic sensor data. Finally, Chryssolouris and Demroese [20] sited the use of force, acoustic and temperature information in recognizing tool wear through neural nets. They also indicated that relearning of the system was required for substantially different cutting conditions.

Controller Response

The influences of the end milling process are shown in Figure 2. All of the controller variables are encapsulated by rectangular boxes at the bottom of the figure. Cutter runout, i.e. tool eccentricity, is typically unwanted, but can only be minimized during set-up of the cutter in its tool holder. The achieve events are ellipses and the prevent events are squares. All other parameters influence these goals in a positive or negative manner. For instance, if the feed per tooth is increased, then the surface finish is degraded and the cutting force is increased. The QPA control structure wants to achieve or prevent events during machining, thus it uses the influence diagram to trace from an event to a controller that can influence that particular event in the desired positive or negative fashion. When conflicts arise, it requires expert knowledge to rank the events in order of importance. For end milling, the following rank is suggested:

1. Shank failure
2. Tooth failure
3. Tool wear failure
4. Chatter
5. Tool deflection
6. Surface finish
7. Maximum feed rate

Control action is initiated when an event is occurring or when the desired event is not being achieved. Typically, this action consists of increasing, decreasing or holding constant the feed rate, spindle speed or depth of cut during each QPA sampling interval. Data from the sensors, examples being cutting force, spindle speed, feed rate and acoustic emission, is collected by the QPA system during each time interval and is used to determine the state of each of the events. If unwanted events are detected, then a planned control action is taken to eliminate that event. Action is also taken to make sure the desired events such as maximum feed rate occur.

V. Simulation of QPA Control of End Milling

QPA control of the end milling process was tested by simulation, using an experimentally validated end milling model, described in Section IV, that is capable of simulating workpiece geometry changes, cutter deflection, and tooth and shank failure. In the simulations, the x feed rate input command signal was determined by the QPA controller, in response to the x and y cutting force, the feed rates, and the spindle speed. QPA used this "sensed" information to determine if any prevent events were occurring, then through the experts encoded knowledge, executed the appropriate control to lower the feed rate. Once prevented, QPA increased the feed rate or held it constant, depending on the band limit around the particular event in question. A simplified QPA control system was tested here to validate the concept of QPA being applied to the

end milling process. The only events that were considered were tooth and shank failure and tool deflection.

One simulation trial result is presented here. Table 1 lists the trial, the geometry change associated with it, and the controller action. Table 2 gives the controller limits for trial one. Figure 7 shows the workpiece geometry for the cut. The simulation is run assuming the cutter is starting in an existing cut. Therefore, the force starts at zero and increases to a constant DC value without going through the typical force transients associated with the entry of the cutter into the side of the workpiece. In this simulation, the QPA controller is trying to achieve maximum feed rate while preventing tool shank failure, tooth failure and part out-of-tolerance. The tool shank failure is associated with the total force on the end of the cutter. If this force exceeds a certain limit, then the cutter is in imminent danger of failure through bending. The QPA response to this is to reduce the feed rate when the total force reaches a set limit. The tooth failure occurs as a result of overloading an individual tooth edge on the end mill. This overload condition can be detected by measuring the feed rate and the spindle speed and calculating the feed per tooth in inches. If this value is above a set limit, then the QPA reduces the feed rate so damage will not occur. Tolerance conditions are determined from the cutting force perpendicular to the path of the end mill.

All of these prevent events have two process instances associated with them. The maximum level indicates to the QPA system that the feed rate needs to be reduced, while the region between the minimum level and maximum level indicates that the feed rate should be held. The hold region is necessary to keep the feed rate command signal from oscillating from the on/off nature of the controller.

The results of Trial One are shown in Figures 8a and 8b. In this run the axial depth is doubled from 0.25 to 0.5 inches at approximately one second, and the radial depth of cut is held constant at 0.25 inches. Before the axial depth change, the tooth failure prevent event becomes active. The controller response is to limit the feed per tooth and thereby reduces the possibility of tooth failure. After the axial depth change, both the total force and the perpendicular force are above their limits (see Figure 8a). This results in a lowering of the feed rate until the perpendicular force is inside the force band. The feed rate is now held constant until this force is below the minimum value. Once this occurs, none of the prevent events are active and the feed rate is increased until the perpendicular force is once again within the given limits. Figure 8b shows the feed per tooth and the corresponding QPA commanded feed rate for the simulated end milling system.

<table>
<tr><th></th><th>Axial
Depth</th><th>Radial
Depth</th><th>Controlled
Events</th></tr>
<tr><td>Trial One</td><td>0.25" to 0.5"
(step)</td><td>0.25"</td><td>Shank Failure,
Tooth Failure, and
Tool Deflection</td></tr>
<tr><td colspan="4"><u>Cutter and Workpiece Data</u>

4 Flute 38 deg. Helix, HHS, 12.7 mm Dia., 44.5 mm
Length
Dry Cutting at 2000 rpm, Stiffness of 90,200 N/cm
Workpiece is 2024-T8 Aluminum</td></tr>
</table>

Table 1 - Workpiece Geometry and Controllers for the Simulated Cut

Shank Failure	
Total Force Bandwidth	
Upper Limit	200 lbs
Lower Limit	150 lbs
Tooth Failure	
Feed per Tooth Bandwidth	
Upper Limit	0.0035 in
Lower Limit	0.0030 in
Tool Deflection	
Perpendicular Force Bandwidth	
Upper Limit	130 lbs
Lower Limit	100 lbs

Table 2 - Controller Bandwidths for Trial One

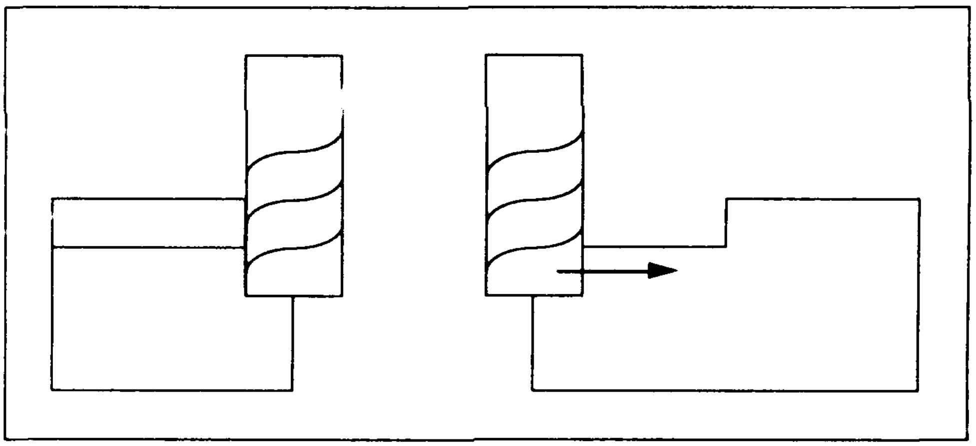


Figure 7 - Milling Cut with an Axial Depth Increase

VI. Experimental Implementation of QPA

The success of any control system is dependent on the interface between the plant and the control components. The QPA system considered here requires interfacing a CNC machining center with sensors, signal conditioning filters, data collection equipment, and a computer for analog to digital (A/D) and digital to analog (D/A) conversion. In addition, the computer must be fast enough to process (sense and control) QPA knowledge with minimal time delays, and output control signals to the machining center for control of the spindle speed and the slide feed rate. The strategy and problem areas of implementation are discussed below.

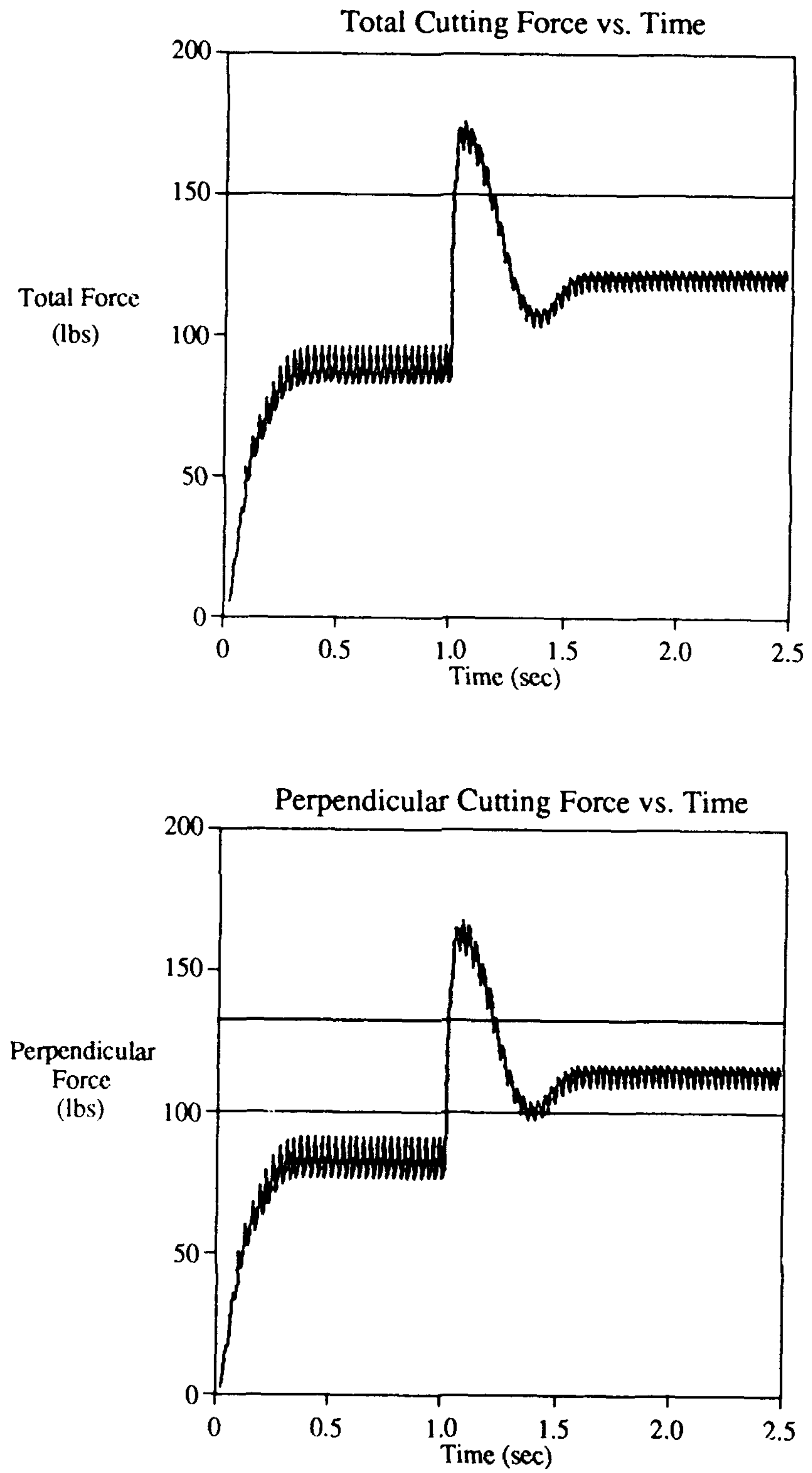


Figure 8a - Results from Trail One (Total and Perpendicular Forces)

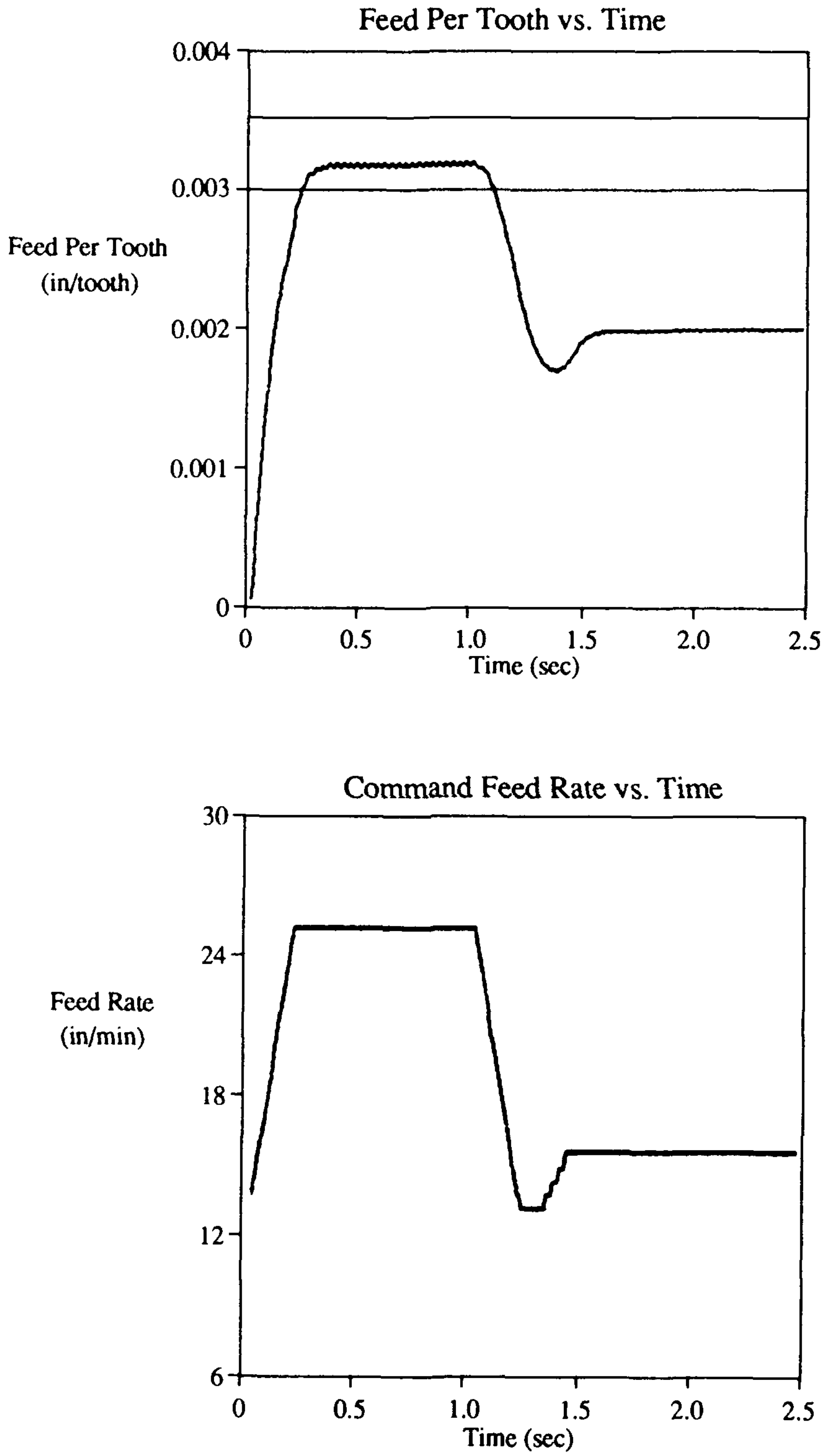


Figure 8b - Results from Trial One (Feed Per Tooth and Feed Rate)

A Fadal VMC40 3-axis machining center is to be used to experimentally test QPA. Figure 9 shows the Fadal machining center with the various important components labeled. The spindle is powered by a 15 horsepower AC motor capable of speeds up to 10,000 RPM. The slides are controlled by DC servo motors systems. Like the majority of the commercial CNC machines, the feed drive command signals are inaccessible, however, there are override potentiometers available for both the spindle speed and feed rate. The spindle speed override pot can vary the spindle speed from 0 to 200 percent while the feed rate override pot has a range of 0 to 150 percent. The pots enable QPA to control the feed rate and spindle speed within the mentioned ranges.

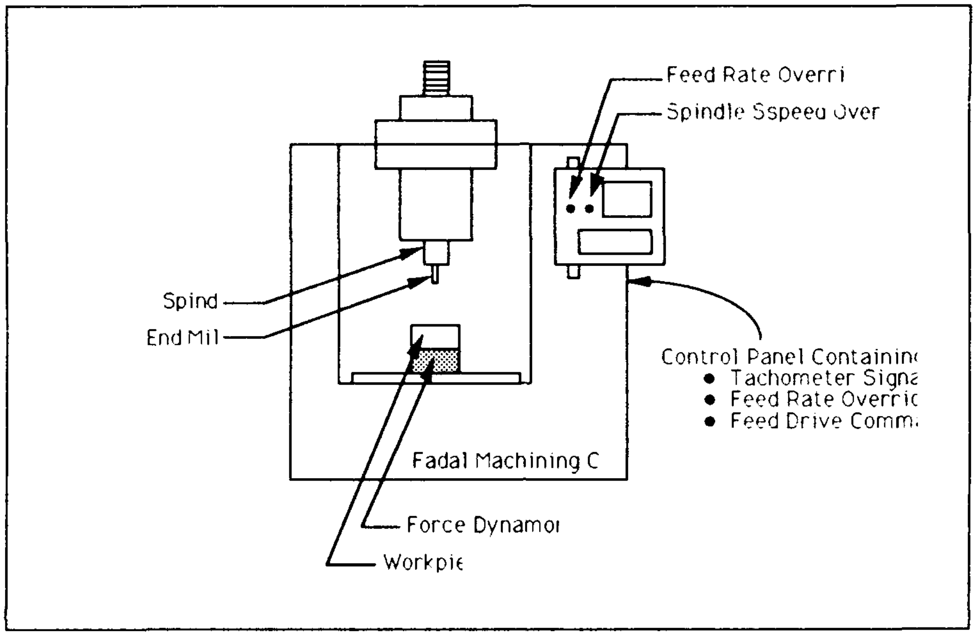


Figure 9 - Fadal 3-Axis CNC Machining Center

The feed rate override potentiometer was tested to calibrate the relationship between the pot voltage and corresponding feed rate percentage. The feed rate percentage is defined as a percentage of feed rate specified in the CNC program. The pot voltage is independent of the programmed feed rate. The tachometer signal, used to obtain the feed rate values, was tested with an LVT to verify the systems velocity tach signals for the x,y, and z slide speeds. To calibrate the feed rate override pot it was first disengaged using a code in the CNC program, and the tachometer voltage for the programmed feed rate read. From this voltage, the tachometer gain was found to be 29.154 (in/min)/volt. Next, the pot was enabled and CNC program was written to move the slide back and forth at the same feed rate as in the previous test. During the execution of the CNC program the feed rate override pot was varied and the corresponding pot voltage and tachometer voltage recorded. From the known voltage at 100 percent and the recorded voltages, a percentage was calculated. During normal QPA operation the calibration curve is used to supply the proper voltage to the CNC's microprocessor.

The sensors that are available to QPA include the slide tachometers and a piezoelectric force transducer. The tachometers supply the information needed to calculate the feed rate. The Fadal machining center has existing tachometer signals readily available from the control panel at the back of the machine. These tachometer signals are used as a velocity feedback to the DC servo feed drive controller boards. There is difficulty, however, when trying to measure the spindle speed. There is no readily available tachometer and the spindle structure prohibits a simple mounting of one. For this work, the spindle speed is considered to be a constant. An encoder could be used if a more accurate measurement is required, but care must be taken since

the surrounding operating conditions are not ideal. The encoder must be capable of accurate measurements while contending with chips and coolant from the cutting.

To measure the x and y cutting forces, a Kistler model 9257A three-dimensional force dynamometer is used. This is a piezoelectric instrument which is capable of reading dynamic force values. The drift in the signals for steady state forces becomes noticeable after a couple of minutes. For our testing, this does not present a problem because the cutting runs are only 6 to 10 seconds long. A charge amplifier is also used to obtain voltage signals proportional to force with a final sensitivity of 50 lbs/volt.

Low-pass filters are used to eliminate noise and other high frequency content from the sensor data (see Figure 10). A third-order Butterworth configuration is incorporated to offer a sharp -60 db/dec attenuation after the breakpoint frequency and an amplitude ratio of zero decibels at low frequencies. A breakpoint frequency of 10 Hertz is used to eliminate both high frequency noise and the majority of the oscillations that occur naturally at the tooth frequency. Recall that the tooth frequency depends on the spindle speed. For the algorithms that are tested, the high frequency content of the force signal is not needed, allowing bandwidths for the total force limits and perpendicular force limits to be reduced. However, the high frequency content will likely be needed if QPA is going to monitor the more complex problems such as chatter and tool wear. When the more complex algorithms are implemented, filters designed with higher breakpoint frequencies can be used to obtain the necessary high frequency content. Higher sampling rates will also be needed, however, to prevent any aliasing that might occur.

A personal computer equipped with a data acquisition system is needed to run QPA and convert the sensor data from analog to digital. For this work, an IBM compatible computer with a 80386 microprocessor is used. A MetraByte DAS-20 Data Acquisition board was installed in the computer to perform the analog to digital (A/D) conversions of the sensor data and also the digital to analog (D/A) conversions of the override signal. Figure 10 shows a block diagram of the setup of the computer and storage systems. The QPA control program is shown in the far right block in the figure. The program is written in Fortran and is run on the personal computer. The QPA program controls the controller output sampling rate and the data acquisition.

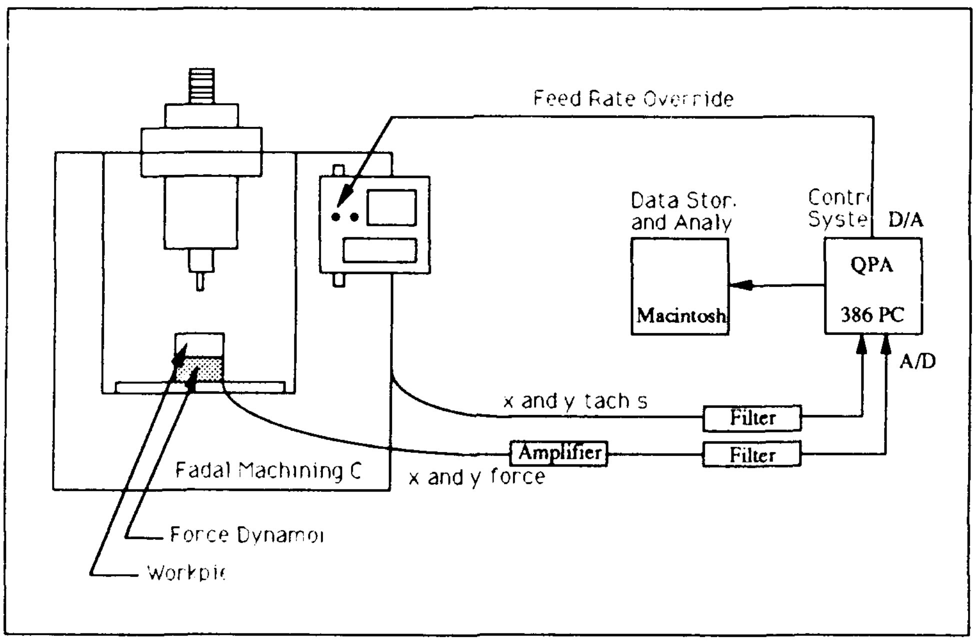


Figure 10 - Block Diagram of Experimental Setup

The successful adaptive control of the end milling process requires a controller that is capable of updating the feed drive and spindle speed many times a second. The QPA control system used in the simulation did not meet this criterion. At best, the simulation QPA control program would have a control cycle time in the 5 second range. To perform the experimentation on the Fadal machining center, a new controller program had to be developed. The new controller was also developed on a PC, but written in Fortran. This allowed the use of the DAS-20 drivers to perform all of the data acquisition tasks. The new controller is based on QPA and contains the same control logic. From the experimental testing, the speed of the experimental controller was found to be capable of a control cycle speed up to 1000 Hertz. With this kind of speed, the experimental QPA should be capable of detecting and responding to many of the undesired events. However, as more complex detection algorithms are programmed, the speed of the controller will decrease due to the increased computer time needed for the algorithms.

The control logic used for the experimental controller is the same as that for the QPA program used in the simulation. There are a few additions, however, that need to be added to the simulation QPA controller to implement it on an actual machining center. These include the initialization of the data acquisition system and feed rate override voltage. There must also be some logic that decides when the controller should finish. For experimental runs, a finish time is used that defines the end of the cut. The experimental code also stores force and feed rate data and allows the user to display various plots at the end of the cut. The following is a detailed description of the experimental control logic:

a) First, a welcome screen is displayed and the DAS-20 is initialized.
b) To prevent any damage to the machine, the feed rate override potentiometer is initially set to zero percent using the `STOP` subroutine.
c) The data file is then input containing all the information on the controllers bandwidth limits, sampling and controlling rates, data file names, and CNC programed values of feed rate and spindle speed. The subroutine `INPUT` performs this task.
d) The current time is calculated using the PC's system clock.
e) All sensors are read and converted from voltage levels to the correct units. The subroutine `DO_ADC` performs one analog to digital conversion on the specified input channel. The data is also copied to a two-dimensional array for later disk storage.
f) The `DECIDE` subroutine then determines if there should be a change in the controller set points. It returns a value equivalent to increase, decrease, or hold.
g) If there is a change in feed rate needed, the `DO_DAC` subroutine calculates the corresponding voltage increase of the control signal and performs the digital to analog conversion.
h) If the current time is less than the finish time specified, the program loops back to step (d) and continues from there. If the current time is equal to the finish time, the program sets the feed rate override potentiometer to zero percent and continues to step (i).
i) The program now transfers all the saved data to an ASCII file for future plotting and analysis. Immediate plotting of the data is available from the subroutine `DO_PLOTS` for a preliminary analysis of the data.

The experimental QPA controller described above is developed to maximize the feed rate while monitoring shank failure, tooth failure, and excessive tool deflection. Using the feed rate override potentiometer for the control output signal results in safer testing operations of QPA than if the signal was directly input as the command signal. The potentiometer can override the feed rate with the range of 0 - 150%. Thus, if the upper limit is specified such that catastrophic failure cannot occur, then safe feed rates will result at all times during the testing.

The results of two actual milling cuts are shown and discussed in this section. For both cuts, the QPA controller sampling rate is 100 Hertz and the feed rate update step is 1% of the CNC programmed feed rate. The geometry for the first cut is a slot cut with an axial depth change from 0.1 inches to 0.25 inches approximately 6 seconds into the cut. Table 3 gives the controller limits of the first cut for the different undesired events monitored by QPA. The tooth failure and tool deflection limits are set to conservative values during the initial testing. Figures 11a and 11b show the resulting total and perpendicular forces and the associated feed per tooth and feed rate plots. From the plots, it is observed that the tooth failure mode limits the feed rate before the axial depth change. Once past the axial depth change, the upper perpendicular force limit is exceeded, i.e. tool deflection mode becomes active, and the feed rate must be decreased to keep the part within the tolerance limits. From the plot of perpendicular force, the time needed to lower the force to within the bandwidth after the axial depth change is approximately 0.5 seconds. This time is similar to the reaction times in the simulation trials.

Shank Failure	
Total Force Bandwidth	
Upper Limit	220 lbs
Lower Limit	180 lbs
Tooth Failure	
Feed per Tooth Bandwidth	
Upper Limit	0.00165 in
Lower Limit	0.00135 in
Tool Deflection	
Perpendicular Force Bandwidth	
Upper Limit	55 lbs
Lower Limit	45 lbs

Table 3 - Controller Bandwidths for Cut One

The second cut involves the same workpiece geometry as the second simulation trial. There is an axial depth change from 0.25 inches to 0.50 inches while the radial depth is half the cutter diameter, 0.25 inches. The controller bandwidths are also the same except for the perpendicular force limits. These limits are shown in Table 4. The results of the second experimental cut are shown in Figures 12a and 12b. Comparing these to the simulation results of Figures 8a and 8b, similar total force, feed per tooth, and feed rate values are achieved before the axial depth change. The experimental perpendicular force before the axial depth change is lower than the simulated force because of the two different cutting orientations. The simulated cuts assume a down milling cut geometry, while the experiments use an up milling geometry, where the cutting tool rotates in the reverse direction as in the figure. Before the axial depth change, the limiting condition is the tooth failure mode. After the axial depth change, the perpendicular force exceeds the upper limit as in the simulation, and the controller reacts by decreasing the feed rate so the force is within the acceptable bandwidth.

The stability of the QPA control strategy is related to an effective gain of the controller, which is the product of the feed rate update increment and controller speed. Throughout the experimental testing, various gains were used. It was noticed that the QPA controller was stable for gains of 5, 10, 20, and 50 (in/min)/sec with an axial depth of 0.15 inches and radial depth of

0.5 inches. When a gain of 50 (in/min)/sec was used along with an axial depth of 0.25 inches, the QPA controller operated in a limit cycle. The spindle speed for all the various cuts was 2000 RPM. It should be noted that the gain value was also very important when determining how fast QPA can respond to prevent damage to the machine.

Shank Failure	
Total Force Bandwidth	
Upper Limit	200 lbs
Lower Limit	150 lbs
Tooth Failure	
Feed per Tooth Bandwidth	
Upper Limit	0.0035 in
Lower Limit	0.0030 in
Tool Deflection	
Perpendicular Force Bandwidth	
Upper Limit	77 lbs
Lower Limit	63 lbs

Table 4 - Controller Bandwidths for Cut Two

The problem in analyzing the controller using the effective gain term is that the overall system gain is also a function of the volume of material that is being removed, with higher volume rates leading to higher system gains. This causes the system stability to be dependent on the amount of material being removed as well as the controller gain. In addition, the system also has a non-linear relationship between the force and the feed rate. For a known steady state cutting situation, some nonlinear analysis could be done, however, if the cutting conditions change drastically the analysis may provide poor results.

VII. Conclusions and Recommendations

The purpose of this research was to apply and evaluate the Qualitative Process Automation control strategy to the end milling process. To accomplish this, a comprehensive investigation of the end milling process was performed to obtain a better understanding of the problems that may arise during a cut. Various algorithms for detecting the problems and preferred controller reactions were also examined. With this information a knowledge base was created for the end milling process for use with QPA.

The QPA controller was first tested through simulation with a program modeling the end milling process. The simulations showed that the QPA controller was capable of maintaining a maximum possible feed rate through various transient conditions while preventing undesired events such as shank failure, tooth overload, and excessive tool deflection. However, there were concerns about the control speed of the QPA program used in the simulation work. During the simulations, the controller was being updated every 5 seconds, approximately, which was not acceptable for real time experimental testing.

An experimental QPA controller was developed, allowing a user defined control speed down to approximately 1 millisecond. This controller was tested using a Fadal 3-axis machining center. The results for the experimental work resembled the predictions obtained through the simulation. The experimental QPA controller maximized the feed rate while preventing the

undesired events described in the control program. It was found that if the control cycle was too fast, the system went unstable, while too long a control cycle would prevent the controller from reacting quickly to serious problems that might arise. It was also noted that the feed drive system of the CNC machining center was too slow to allow the QPA control system to prevent catastrophic collisions between the tool and workpiece, should they arise.

The work performed in this research is a start toward the introduction of a complete intelligent control system for the end milling process and offers an adequate platform for future expansion. For the algorithms tested, the QPA control strategy is found to be very effective at minimizing cutting time. However, since the ultimate goal is to have a fully autonomous machining center, algorithms to detect tool damage, chatter, and excessive tool wear must be implemented into the control program. The majority of these algorithms involve much more complex data analysis, which would consume considerable amounts of computer time. The advancement of sensor technology would also provide methods of detecting more complex problems.

More complex cutting operations should be performed on the existing system to further evaluate the QPA control strategy. These should include cutting paths in two or more directions. To accomplish this, all feed rate values will be needed to calculate a velocity vector. This velocity vector will then be used to determine the perpendicular force on the cutter with respect to its direction for use in detecting excessive tool deflection.

Information from the CNC program and workpiece geometry would provide helpful knowledge for the controller program when determining the process state during the cut. For example, the controller must know when the cutting tool is in free air between cutting passes and when the tool is being changed. The controlling of the machining center, as it stands presently, is very limited. The feed rate override potentiometer provides an opening for the QPA controller to be applied on the Fadal machining center. Direct access to the feed drive and spindle drive command signals is necessary if the performance of QPA is to be improved.

Lastly, a rigorous attempt must be made to analyze the stability of the QPA control strategy. The effective QPA controller gain, which is a function of control rate and update increment, has a great effect on the stability of the process. The rate of volume of material removal also affects the system gain and is very important in determining the system stability and performance when being controlled by QPA.

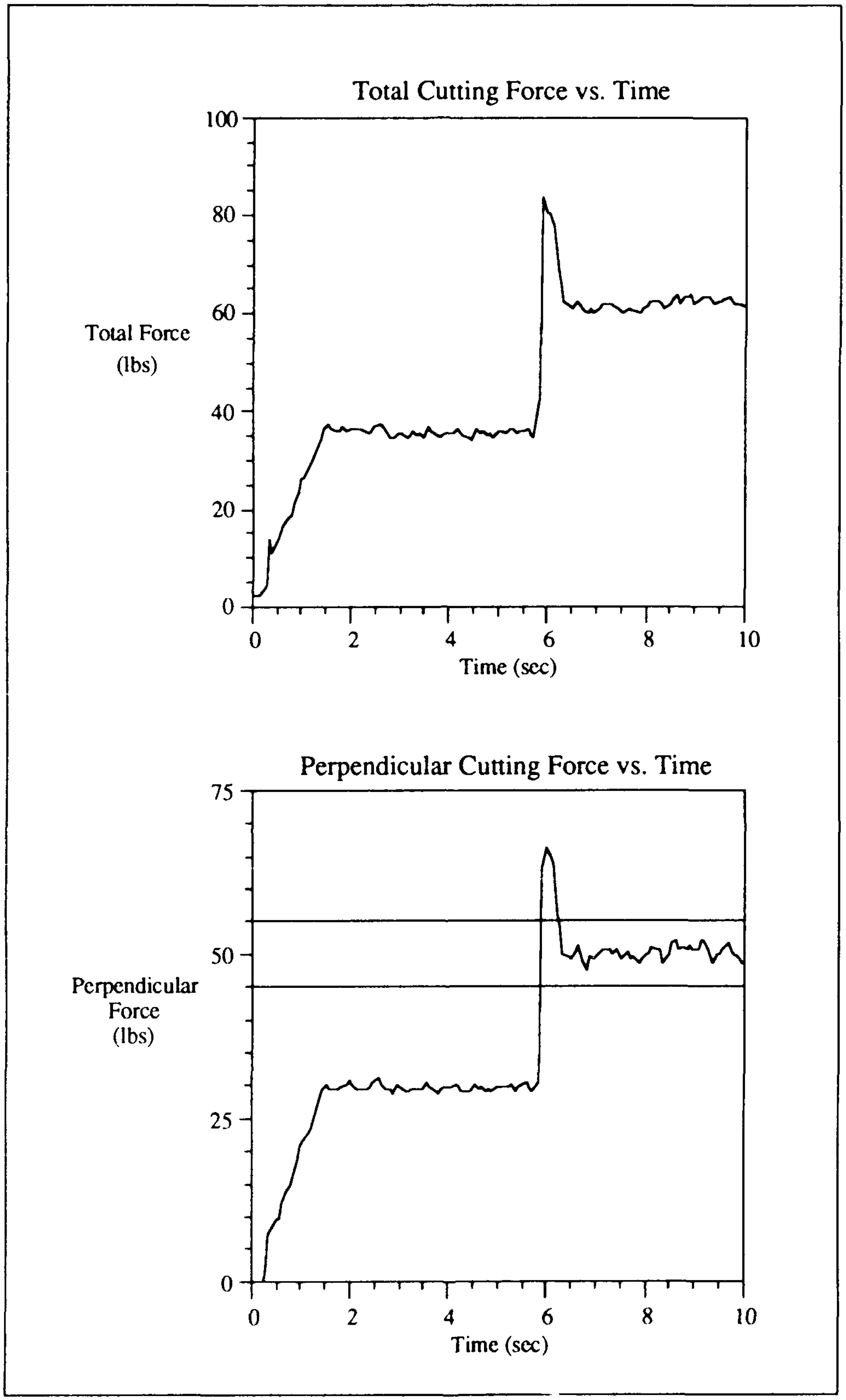


Figure 11a - Results from Experimental Cut One (Total and Perpendicular Forces)

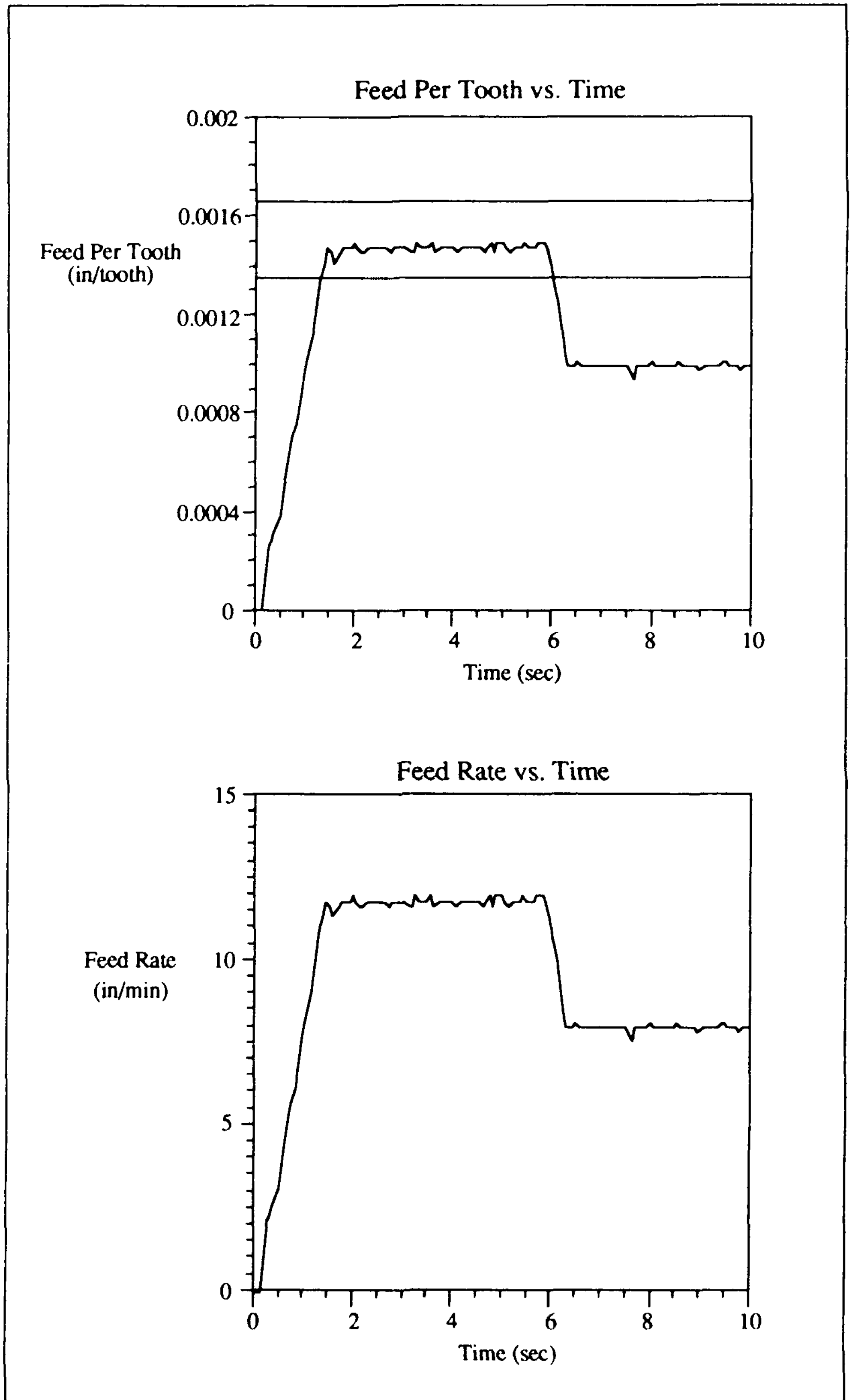


Figure 11b - Results from Experimental Cut One (Feed per Tooth and Feed Rate)

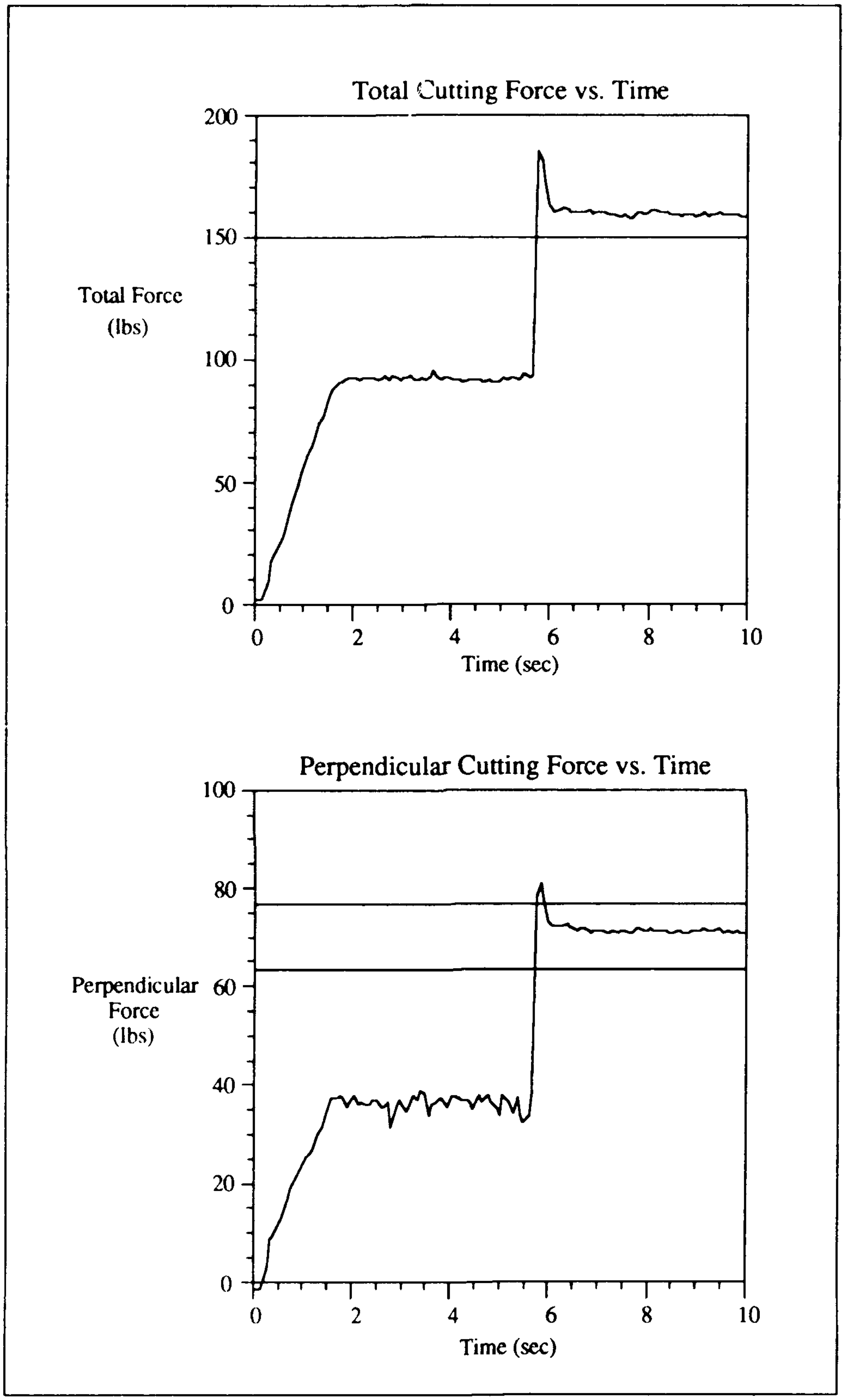


Figure 12a - Results from Experimental Cut Two (Total and Perpendicular Forces)

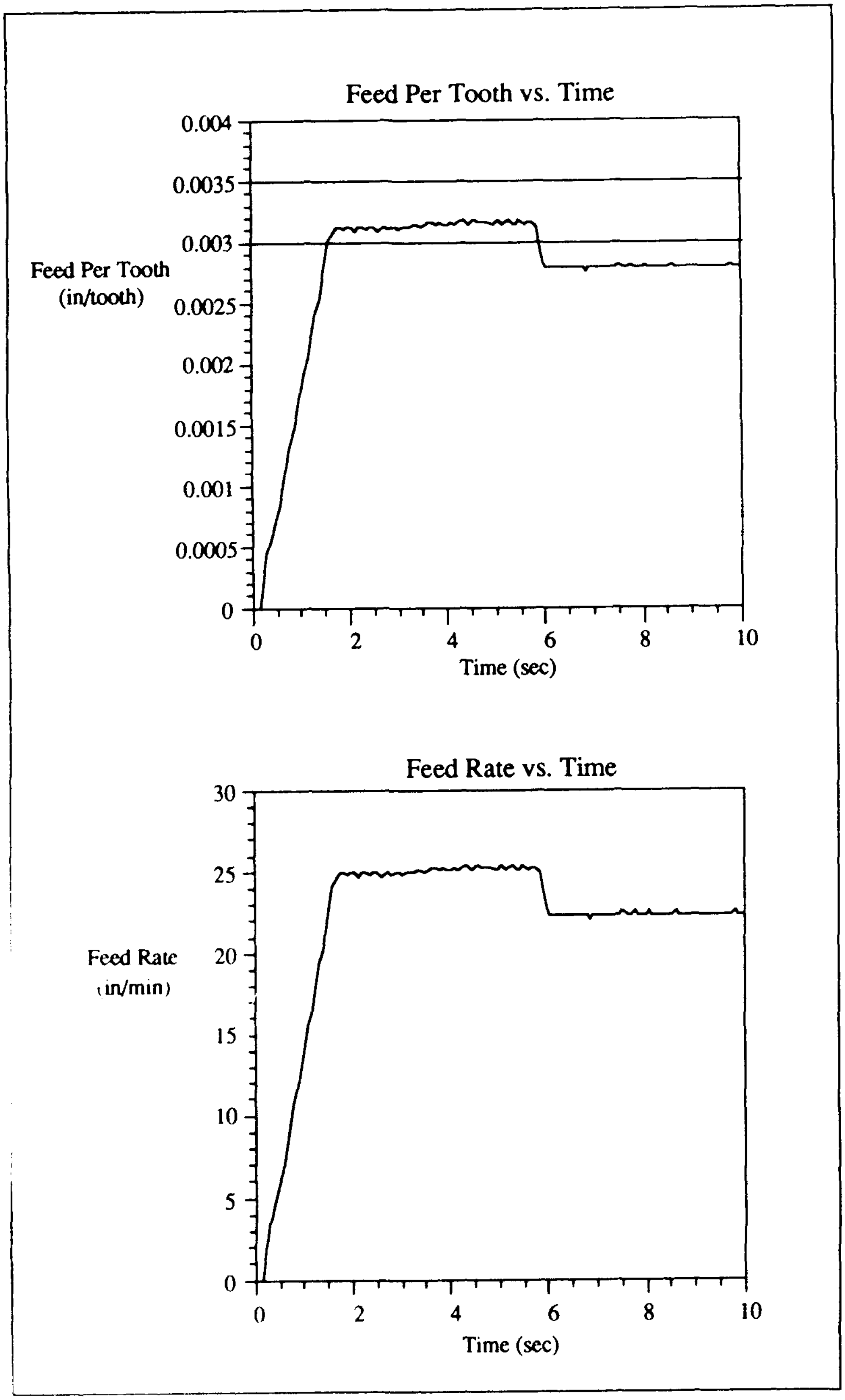


Figure 12b - Results from Experimental Cut Two (Feed per Tooth and Feed Rate)

References

[1] Abrams, F., P. Garrett, T.Lagnese, S. LeClair, C.W. Lee and J. Park, "Qualitative Process Automation for Autoclave Curing of Composites", AFWAL/MLTC Interim Report for the Period 15 October 1985-15 May 1987, AFWAL-TR-87-4083.

[2] Fussell, B.K. and K. Srinivasan, "An Investigation of the End Milling Process Under Varying Machining Conditions", Submitted for publication to ASME Journal of Engineering for Industry, 1986.

[3] Forbus, K., "Qualitative Process Theory", in Qualitative Reasoning About Physical Systems, edited by D.G. Bobrow, MIT Press, pp. 85-168, 1982.

[4] Matejka, R.F. and T.J. Lagnese, "A Representational Language for Qualitative Process Control", 1988.

[5] Fussell, B.K., Modeling and Adaptive Force Control of End Milling Operations, Ph.D. Thesis, Dept. of Mechanical Engineering, The Ohio State University, Columbus, Ohio, 1987.

[6] Altintas, Y., I. Yellowley and J. Tlusty, "the Detection of Tool Breakage in Milling", ASME Winter Annual Meeting, Miami, Florida, 1985, pp. 41-48.

[7] Altintas, Y. and I. Yellowley, "In-Process Detection of Tool Failure in Milling Using Cutting Force Models", ASME Winter Annual Meeting, Boston, MA, 1987, PED-Vol. 26, pp. 1-16.

[8] Lan, Ming-Shang and Y. Naerkeim, "In-Process Detection of Tool Breakage in Milling", ASME Journal of Engineering for Industry, August 1986, Vol. 108, pp. 191-197.

[9] Melkote, R. and D.L. Taylor, "An Implementation of a Rule Based Selection of Milling Cutters, Feed Rates, and Spindle Speed", Proc. of the ASME Winter Annual Meeting, Computers in Engineering, pp. 427-432.

[10] Roark, Raymond J., and Warren C. Young, Formulas for Stress and Strain, 5th Edition, McGraw-Hill, New York, 1975, p. 290.

[11] Marks Standard Handbook for Mechanical Engineers, 8th Edition, Edited by Theodore Baumeister, pp. 13-53.

[12] Smith, S. and J. Tlusty, "NC Programming for Quality in End Milling", 16th NAMRC, May 1988, SME, pp. 279-286.

[13] Shigley, J.E., and L.D. Mitchell, Mechanical Engineering Design, McGraw-Hill, New York, 1983.

[14] Smith, S. and J. Tlusty, "Update on High-Speed Milling Dynamics", ASME Winter Annual Meeting, Boston, MA, PED-Vol. 25, 1987, pp. 153-165.

[15] Marks, J. and M.A. Elbestawi, "Development of Machine Tool Condition Monitoring System Using Pattern Recognition," ASME Winter Annual Meeting, Chicago, Ill., 1988, PED-Vol. 33, pp. 89-98.

[16] Dornfeld, D.A. and C.S. Pan, "Determination of Chip Forming States Using a Linear Discriminant Function Technique with Acoustic Emission," 15th NAMRC, May 1985, pp. 299-303.

[17] Rangwala, S. and D. Dornfeld, "Integration of Sensors via Neural Networks for Detection of Tool Wear States", Proc. of the ASME Winter Annual Meeting, 1987, pp. 109-120.

[18] Emel, E. and E. Kannatey-Asibu Jr., "Tool Failure Monitoring in Turning By Pattern Recognition Analysis of AE Signals", ASME Winter Annual Meeting, Boston, MA, PED-Vol. 26, 1987, pp. 39-57.

[19] Emal, E. and E. Kannatey-Asibu, Jr., "Acoustic Emission Monitoring of the Cutting Process Negating the Influence of Varying Conditions", Proc. of the ASME Winter Annual Meeting, 1988, pp. 63-74.

[20] Chryssolouris, G. and M. Domroese, "Sensor Integration for Tool Wear Estimation in Machining", Proc. of the ASME Winter Annual Meeting, Chicago, Ill., 1988, pp. 115-123.

U.S. Government Printing Office 648-127